HIGH ENERGY MUON COLLIDERS *

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Abstract

A plausible "straw-man" scenario and collider ring parameter sets are presented for future energy frontier muon colliders in symbiotic facilities with e^+e^- and hadron colliders: 1.6-10 TeV "mu-linear colliders" (mu-LC) where the muons are accelerated in the linacs of a TeV-scale linear e^+e^- collider, and a 100 TeV Very Large Muon Collider (VL**M**C) that shares a facility with a 200 TeV Very Large Hadron collider (VLHC) and a 140 TeV muon-proton collider.

1 INTRODUCTION

Muon colliders [1, 2] are a potential option for exploring and extending [3, 4, 5] the energy frontier of experimental high energy physics (HEP). Research on muon colliders is at the stage of feasibility studies.

Muons are leptons with a mass 206 times larger than the electron. It follows that their collisions are expected to display similar physics to that of electrons at the same energy but, in contrast to electrons, the natural energy limitation for *circular* muon storage rings due to synchrotron radiation is not reached until center-of-mass energies $E_{CoM} \sim 100$ TeV, where the synchrotron radiation energy loss has finally risen to become comparable to the beam power. On the negative side, muons are unstable, decaying with a rest-frame lifetime of 2.2 microseconds into an electron and two neutrinos. To cope with these decays, the muon bunches must be frequently replenished and then quickly cooled, accelerated and collided, and allowance must be made for dealing with the decay products.

This paper discusses a plausible scenario where muon colliders could work in concert with e^+e^- linear collider and hadron collider technologies to continue the historically exponential progress in lepton collider energy reach that is embodied in the well-known "Livingston curve". This scenario will be examined further in the "energy frontier muon collider" sessions at Snowmass 2001 [6].

The scenario includes 3 new energy frontier facilities: 1) a TeV-scale linear e^+e^- collider where the linacs are also used to accelerate muons for a 1.6-10 TeV muon collider (mu-LC), 2) a symbiotic frontier lepton-hadron facility with a 100 TeV Very Large Muon Collider (VLMC), a 200 TeV Very Large Hadron Collider (VLHC) and a 140 TeV muon-proton collider, and 3) a 1 PeV (i.e. 1000 TeV) *linear* muon collider.

The first two of these facilities will be discussed in this paper and table 1 gives "straw-man" parameter sets for both mu-LCs and a 100 TeV VLMC. The technology for the 1 PeV linear muon collider is very much more speculative. A somewhat plausible 1 PeV final focus parameter set has been presented by Zimmermann [7] but this collider will require, amongst other daunting challenges, extremely cost efficient acceleration, e.g. with plasma acceleration, that still preserves small beam emittances.

As a preliminary comment that applies to both mu-LCs and VLMCs, the high performance ionization cooling channel is the signature technology of muon colliders and is the dominant technical challenge for both types of muon colliders. The initial phase space density of the muon cloud from pion decays needs to be increased by approximately 6 orders of magnitude to produce muon bunches suitable for acceleration and collision.

Research so far on the cooling channel has produced: a) general theoretical scenarios and specifications to reach the desired 6-dimensional emittance, b) detailed particle-by-particle tracking codes (modified GEANT, ICOOL) and (new) higher order matrix tracking code (modified COSY-infinity) and a (new) wake field code interface, c) engineering designs of small subunits of cooling channels, d) neutrino factory designs with approximately one order of magnitude of *transverse* cooling, and e) a "ring cooler" design for a cooling demonstration experiment, by Balbekov of FNAL, with a predicted full 6-dimensional cooling factor of approximately 32.

However, the above-listed areas of progress in muon cooling R&D have yet to be amalgamated to "build the complete muon collider cooling channel on a computer". This should clearly be considered the main short-term priority for muon collider research and the technology of muon colliders will become much more plausible once this is accomplished.

The major technical issues that are relatively specific to energy frontier muon colliders are 1) affordable acceleration to the TeV energy scale and above, 2) collider rings with very large beam demagnifications at the final focus, 3) more serious backgrounds from muons in the experiment's detector and 4) restrictions imposed by neutrino radiation [8], which rises sharply with beam energy.

The concept of mu-LCs was first presented by Neuffer *et al.* [9] in 1996. It works better for larger, superconducting cavities such as in the TESLA collider, since these can transport a larger bunch charge. For reasonable assumptions, the specific luminosity scales approximately as the square root of the bunch charge.

The simplest potential option for incorporating a muon collider into to a TeV-scale linear collider facility is to simply accelerate both muon signs through both the electron and positron linac and inject them into a muon collider

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storage ring to create an "energy doubler" relative to the e^+e^- collider center-of-mass energy. Unlike electrons, the muons can be bent and recirculated several times through the linacs to give higher energy muon colliders. As other options, beam-lines for either a neutrino factory or an s-channel $\mu^+\mu^-$ Higgs factory might be bled off the linac. The choice of muon collider energy and any other add-ons can be flexibly determined based on future high energy physics results from the Tevatron, LHC and neutrino experiments.

The mu-LC parameters in table 1 represent a range of "straw-man"parameter sets for mu-LCs built up from either the TESLA or NLC e^+e^- linear colliders; the individual parameter sets can be found at [6].

The muon bunch repetition rate for each mu-LC parameter set and, hence, the luminosity was constrained to cause negligible neutrino radiation, where "negligible" was operationally defined to be a maximum of less than 0.001 mSv/year as an angular average around the plane of the collider ring and less than 0.01 mSv/year in any direction, to be compared to the U.S. legal off-site limit of 1 mSv/year (i.e. 100 mrem/year).

The 100 TeV parameter set obtains a luminosity of $\mathcal{L}= 2\times10^{35}\,\mathrm{cm}^{-2}.\mathrm{s}^{-1}$ per detector (there might well be 2 detectors) by assuming beam currents limited only by beam power. This assumption could be met only at an isolated or elevated laboratory site that either greatly minimizes or totally eliminates any human exposure to the neutrino radiation disk.

On balance, the technical difficulties for a VLMC are not much worse than for lower energy muon colliders, particularly as slightly *less* beam cooling is required, although some areas are more demanding, as follows.

Forty-four megawatts of synchrotron radiation are produced for the parameters of table 1, i.e. slightly more than twice that produced at LEP-II and comparable to the energy dumped by decay electrons.

Encouragingly, an attractive final focus lattice design with $\beta^* = 4.8$ mm now exists [10] for a 30 TeV muon collider, making plausible a 100 TeV final focus with $\beta^* = 8$ mm.

The acceleration for the VLMC might plausibly be provided by approximately 250 passes per beam through several recirculating lattices with large momentum acceptance fixed field superconducting magnets ("FFAGs") and approximately 200 GeV of superconducting rf cavities, all located in the collider ring tunnel. This scenario allows for approximately 50% of the muons to decay during acceleration and, hopefully, a higher energy version of existing FFAG lattices (e.g., [11]) will be designed for the Snowmass 2001 meeting.

A 200 TeV VLHC hadron collider could plausibly be located in either the same tunnel as, or an adjacent tunnel to, the VLMC. In this case, the recirculating rings for muon acceleration could also accelerate the hadron beams for injection at half-energy into the hadron collider ring. Finally, muon-proton collisions at center-of-mass energies up to 140 TeV should also be achievable.

2 SUMMARY

A plausible straw-man scenario and collider ring parameter sets have been presented for future energy frontier muon colliders in symbiotic facilities with e^+e^- and hadron colliders. These will be examined further in the Snowmass 2001 meeting. The extremely high constituent particle energies and luminosities of the parameter sets presented in table 1 continues to suggest that muon colliders could play a central role in exploring and extending the HEP energy frontier.

3 REFERENCES

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Table 1: **Self-consistent muon collider ring parameter sets for Snowmass 2001 studies.** The final column is the 100 TeV Very Large Muon Collider (VLMC) "straw-man" parameter set and the middle column shows the range of parameters for the straw-man parameter sets assuming a muon collider using acceleration from an existing TeV-scale e+e- linear collider linac (mu-LC). The individual parameter sets for the TESLA and NLC mu-LCs are given individually in the 2 following tables. "Straw-man" means that studies and constructive criticism are invited in order to determine the feasibility or otherwise of the parameter sets. For comparison, the first column displays the range of the corresponding parameters from the muon colliders at 0.1, 0.4 and 3 TeV that are discussed in the paper: The Muon Collider Collaboration, *Status of Muon Collider Research and Development and Future Plans*, Phys. Rev. ST Accel. Beams, 3 August, 1999. The parameters in column 1 that were not provided in that reference have been either estimated or reconstructed for consistency with those parameters that were provided.

parameter set **center of mass energy,** $\mathrm{E_{CoM}}$	MCC Status Rep. 0.1 to 3 TeV	mu-LC 1.6 to 10 TeV	VLMC 100 TeV
collider physics parameters:			
luminosity, $\mathcal{L}$ $[10^{34}\,\mathrm{cm^{-2}.s^{-1}}]$	8×10^{-4}→5.0	1.0	20
$\int \mathcal{L}$dt $[\mathrm{fb^{-1}/year}]$	0.08→540	100	2000
No. of $\mu\mu \to \mathrm{ee}$ events/det/year	650→10 000	90→3400	17
No. of 100 GeV SM Higgs/year	4000→600 000	85 000→140 000	4.2×10^{6}
CoM energy spread, $\sigma_{\mathrm{E}}/\mathrm{E}$ $[10^{-3}]$	0.02→1.1	1.8→3.2	0.28
collider ring parameters:			
circumference, C [km]	0.35→6.0	3.0→10.0	200
ave. bending B field [T]	3.0→5.2	5.6→10.5	5.2
beam parameters:			
(μ^- or) μ^+/bunch, $\mathrm{N_0}[10^{11}]$	20→40	0.2→8	7
(μ^- or) μ^+ bunch rep. rate, $\mathrm{f_b}$ [Hz]	15→30	1→650	10
P.S. density, $\mathrm{N_0}/\epsilon_{6N}[10^{22}\mathrm{m^{-3}}]$	1.2→2.4	4.0→36	0.80
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}\mathrm{m^3}]$	170	0.10→12	88
$\epsilon_{6N}[10^{-6}\mathrm{m^3.MeV/c^3}]$	200	0.12→14	104
x,y emit. (unnorm.) $[\pi.\mu\mathrm{m.mrad}]$	3.5→620	0.023→1.8	0.016
x,y normalized emit. $[\pi.\mathrm{mm.mrad}]$	50→290	1.1→14	7.6
long. emittance $[10^{-3}\mathrm{eV.s}]$	$0.81 \to 24$	7.9→83	530
fract. mom. spread, δ $[10^{-3}]$	0.030→1.6	2.5→4.5	0.40
relativistic γ factor, $\mathrm{E}_\mu/\mathrm{m}_\mu$	470→14 000	7600→47 000	470 000
time to beam dump, $\mathrm{t_D}[\gamma\tau_\mu]$	no dump	0.5→1.0	no dump
effective turns/bunch	450→780	630→990	780
ave. current [mA]	17→30	0.20→7.0	3.5
total beam power [MW]	1.0→29	0.81→5.5	110
synch. rad. critical E [MeV]	$5 \times 10^{-7} \to 8 \times 10^{-4}$	$2 \times 10^{-4} \to 0.02$	0.9
synch. rad. E loss/turn [GeV]	$7 \times 10^{-9} \to 3 \times 10^{-4}$	$5 \times 10^{-5} \to 0.03$	13
synch. rad. power [MW]	1×10^{-7} →0.010	$4 \times 10^{-4} \to 0.005$	44
beam + synch. power [MW]	1.0→29	0.81→5.3	160
power density into magnet liner [kW/m]	1.0→1.7	0.012→0.50	0.42
interaction point parameters:			
spot size, $\sigma_{x,y}$ $[\mu\mathrm{m}]$	3.3→290	0.18→1.4	0.36
bunch length, σ_z [mm]	3.0→140	0.53→1.7	8.0
$\beta^*_{x,y}$ [mm]	3.0→140	0.53→1.7	8.0
ang. divergence, σ_θ [mrad]	1.1→2.1	0.13→1.4	0.045
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.010→0.100	0.100
pinch enhancement factor, $\mathrm{H_B}$	1.00→1.01	1.00→1.13	1.11
beamstrahlung frac. E loss/collision	negligible	negligible	1.2×10^{-7}
neutrino radiation parameters:			
collider reference depth, D[m]	10→300	100→600	100
ave. rad. dose in plane [mSv/yr]	2×10^{-5}→0.02	9×10^{-4}	18
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	0.63→1.0	8.4
ν beam distance to surface [km]	11→62	51→87	36
ν beam radius at surface [m]	4.4→24	1.9→6.7	0.075